EA303 WIND TUNNEL
EXPERIMENT I

PRESSURE AND VELOCITY MEASUREMENT

I. Purpose

1. To introduce laboratory and wind tunnel operations procedures.
2. To introduce methods of pressure measurement.
3. To determine the dynamic pressure and velocity in a wind tunnel.
4. To illustrate methods of determining density, viscosity and Reynolds number.
5. To determine calibration curves/constants for the USNA Wind Tunnels.

II. References

1. RAE, W.H. JR and POPE, A. *Low Speed Wind Tunnel Testing*, John Wiley & Sons (New York, 1984)
   a. Wind Tunnels - general discussion: Chapters 1 & 2 (Skip 2.5, 2.15, 2.16)
   b. Manometry, pitot-static tube: 3.1, 3.4
   c. Velocity measurement: 3.10
   d. Turbulence factor: 3.15
   e. Horizontal Buoyancy: 6.3, 6.9
2. Anderson, J.D., Introduction to Flight, McGraw-Hill, 1989, pp. 90-91

III. Introduction

After a wind tunnel is constructed, it is necessary to determine the flow characteristics, i.e., to calibrate the tunnel. Tunnel calibration usually involves determining the tunnel constant, the variation of dynamic pressure and any variation of flow angle in the test section as a function of velocity. The static pressure variation along the longitudinal axis of the test section and the degree of turbulence in the air are also of interest.

IV. Theory

Determination of dynamic pressure and velocity.

Because aerodynamic forces and moments are generally nondimensionalized with respect to dynamic pressure, the determination of the dynamic pressure in the test section is of particular importance. In order to understand the theory used in making dynamic pressure measurements we consider Euler's equation for the steady flow of a nonviscous, homogeneous, continuous fluid in a streamtube. The differential form of Euler's equation is

$$dp + \rho V dV + \rho g dh = 0 \tag{1}$$

where the differential terms refer to the fluid element given in Fig. 1 and where

p = fluid static pressure	A = area
ρ = fluid density	W = weight
V = fluid velocity	g = acceleration of gravity

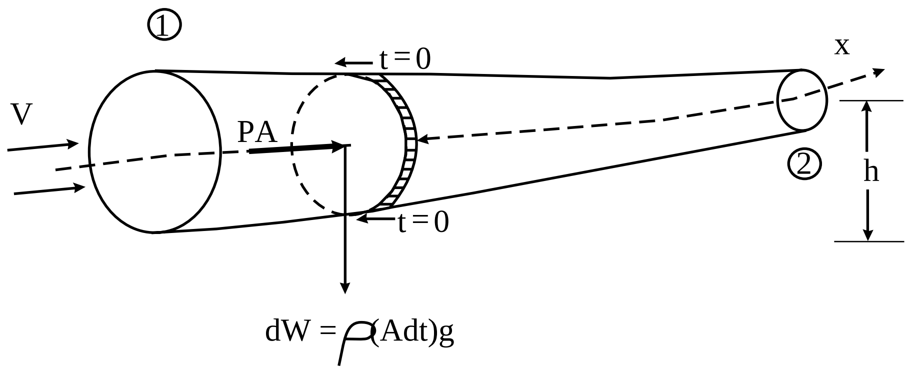

Figure 1. Streamtube.

If we consider an incompressible fluid (ρ = const), the equation can be integrated, i.e., Eq. (1) becomes

$$p + \frac{\rho V^2}{2} + \rho g h = \text{const} \tag{2}$$

where the constant is the same for any position in the stream tube. Here the first item is the static pressure, the second is the dynamic pressure, and the third is the elevation term. Writing Euler's equation at points 1 and 2 and equating we have

$$p_1 + \frac{\rho V_1^2}{2} + \rho g h_1 = p_2 + \frac{\rho V_2^2}{2} + \rho g h_2 \tag{3}$$

Analysis of this equation yields two special equations of interest,

a. the manometer relation for measuring differences in pressure,
b. the Bernoulli equation which represents a special relation between the potential and kinetic energy/unit volume of the flow.

The Manometer Relation

If stations 1 and 2 represent the end points of a column of fluid in a manometer, Eq. (3) applied to the fluid (liquid) at rest ($V_1 = V_2 = 0$) yields (see Fig. 2):

$$p_2 - p_1 = -\rho g (h_2 - h_1) \tag{4}$$

By definition, specific weight is

$$w = \frac{\text{weight}}{\text{Volume}} = \frac{\text{mg}}{\text{Volume}} = \rho g \left[\frac{\text{slug}}{\text{ft}^3}\frac{\text{ft}}{\text{sec}^2}\right] \tag{5}$$

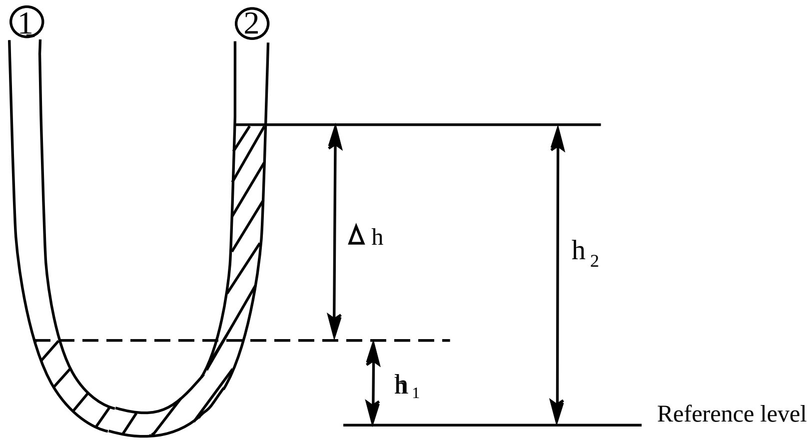

Figure 2. U-tube manometer.

Therefore, the manometer relation becomes:

$$p_1 - p_2 = w(h_2 - h_1) \tag{6}$$

where w is the specific weight of the liquid used in the manometer. For a given pressure differential, a heavier liquid, such as mercury with a specific gravity = 13.56, i.e., 13.56 times as dense as water, shows a smaller manometer height differential. In order to measure small pressure differentials accurately, a light weight fluid is used, e.g., alcohol, s.g. = 0.813.

Manometer tubes are sometimes inclined to enlarge the reading scale. In this case the height, h is equal to the length, ℓ of the inclined column of fluid divided by the sine of the inclination angle as shown in Fig. 3, i.e., $h = \ell / \sin\phi$.

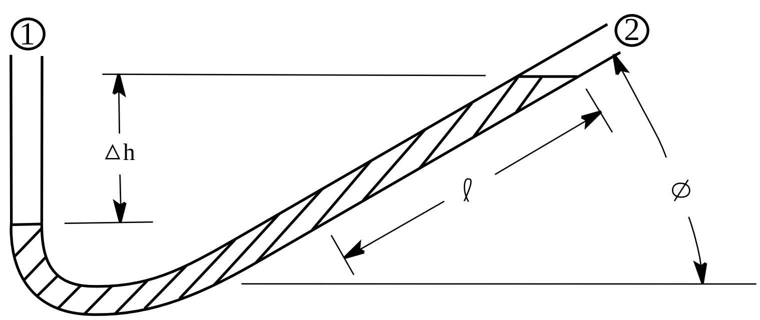

Figure 3. Inclined manometer.

Because of the proportionality of pressure to manometer height, pressure is sometimes indicated in units of length, a practice dimensionally inconsistent because pressure must be force/area. For example, the standard sea level atmosphere reading of 29.92 in Hg indicates that the height differential of a column of mercury connected at one end to a vacuum and at the other end to air at atmospheric pressure is 29.92 inches. A column of alcohol is 13.56/0.804 = 16.89 times as high, or 42.05 feet! Obviously small alcohol heights are capable of measuring very small pressure differences. One inch of alcohol corresponds to a pressure difference of

$$\begin{aligned}\Delta p &= w(h_2 - h_1) = \text{s.g.}(w_{H_20})(h_2 - h_1) \\ &= (0.804)\left(62.4\frac{\text{lb}}{ft^3\,\text{alc}}\right)(1\,\text{alc})\left(\frac{1\,\text{ft}}{12\,\text{in}}\right)\left(\frac{1\,\text{ft}^2}{144\,\text{in}^2}\right) = 0.029\,\text{psi}\end{aligned}$$

Bernoulli' s Equation.

When considering the flow of gases it is generally possible to neglect the effect of small changes in elevation. For example, the flow of air in a streamtube which undergoes a one foot change in elevation results in a pressure change of:

$$\begin{aligned}\Delta p = w\Delta h &= \left(0.002377\frac{\text{slugs}}{\text{ft}^3}\right)\left(32.18\frac{\text{ft}}{\text{sec}^2}\right)(1\,\text{ft})\left(\frac{\text{lb sec}^2}{\text{ft}}\right)\left(\frac{1}{\text{slug}}\right)\\ &= 0.0765\frac{\text{lb}}{\text{ft}^2}\\ &= 0.000532\,\text{psi}\end{aligned}$$

which is quite small. Thus, we can neglect the effect of the elevation term in Eq. ((3)). Euler's equantion then reduces to

$$p + \frac{\rho V^2}{2} = p + q = \text{const} = p_T \tag{7}$$

where $q = 1/2\rho V^2$ is the dynamic pressure and the subscript T indicates total pressure. This is Bernoullis equation which says that the total pressure remains constant along streamtubes for a nonviscous fluid in a steady, one dimensional flow when the effects of change in elevation are neglected.

Bernoullis equation may be written between any two points along the streamtube, e.g., 1 and 2 as shown in Fig. 1 or for points 1 and 2 of Fig. 2, i.e.,

$$p_1 + q_1 = p_2 + q_2 = p_T = \text{const} \tag{8}$$

Pitot-static tube

Equations (6) and (7) suggest a method for determining the velocity of an airstream. Consider the manometer in Fig. 2. The pressure at point 1 must be the same whether measured from the air or the fluid side. The same applies at point 2. Applying Eq. (6) to the manometer in Fig. 2, where point 1 is total pressure, P_T and point 2 is the static pressure, p_s yields

$$p_1 - p_2 = p_T + p_s = q = \frac{1}{2}\rho V^2 = w_{\text{man}}\Delta h_{\text{man}} \tag{9}$$

That is, the difference between total and static pressure is dynamic pressure. If an instrument can be devised to measure this difference directly, then the dynamic pressure is known. Furthermore, if the density of the airstream is known, then the velocity can be calculated, i.e., from Eq. (9) we have

$$V = \sqrt{\frac{2(p_T - p_s)}{\rho}} \tag{10}$$

The most common device used to determine total pressure and static pressure is the pitot-static tube or probe. A standard design and a Prandtl pitot-static tube are shown in Fig. 4.

The orifice at A reads total pressure $p + 1/2\rho V^2$, and the orifices at B read the static pressure, p_s. If the pressures from the two orifices are connected across a manometer, the pressure differential is, of course, $1/2\rho V^2$ from which, knowing the density, the velocity can be calculated.

The pitot-static tube is easy to construct, but it has some inherent errors. If due allowance is made for these errors, a true reading of the dynamic pressure within about 0.1 percent may be obtained.

Experience shows that a pitot tube with a hemispherical tip will read the total pressure head accurately independent of the size of the orifice opening as long as the yaw is less than three degrees. A squared off pitot tube reads the total pressure at higher yaw angles without error, but both square- and round headed pitot tubes suffer errors if they are used at too low Reynolds numbers or too close to a wall.

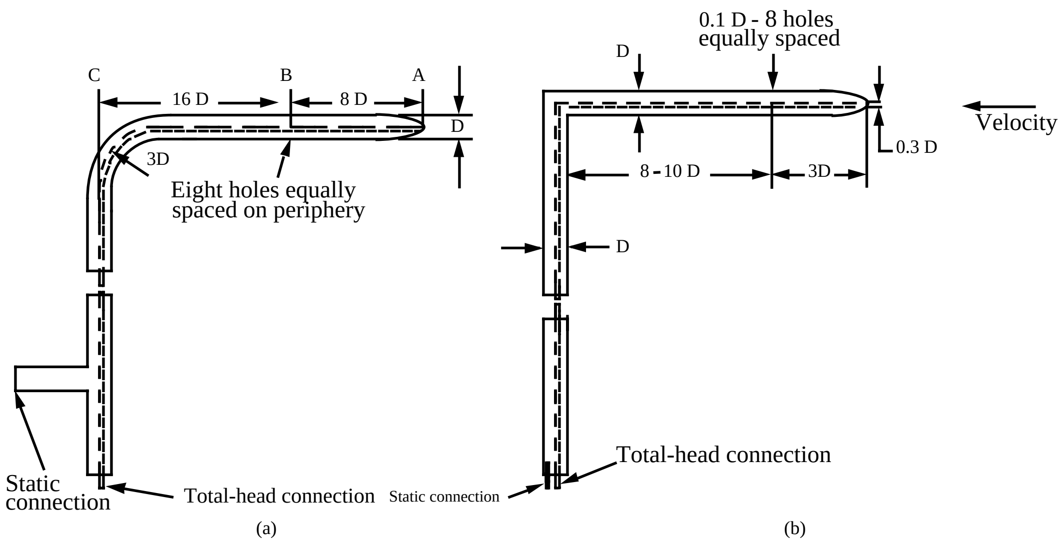

Figure 4. Pitot-static probe; (a) Standard design, (b) Prandtl design.

The static holes in a pitot-static probe suffer from two effects

a. Crowding of the streamlines near the tip reduces the pressure along the shank of the pitot-static tube so that the static pressure at the static orifices is too low. The error is shown in Fig. 5 as a function of yaw angle.

b. A high-pressure region exists ahead of the stem that tends to make the indicated static pressure too high.

These two effects compensate for each other if the static holes are properly located. The standard pitot-static tube does not employ this principle because it requires the static holes to be so close to the tip that small deviations in tip construction or damage to the tip results in a relatively large error in the static pressure reading.

Hence,

1. If a new pitot-static tube is built, either it is designed based on Fig. 4a and its static pressure readings corrected using Fig. 5, or the Prandtl design is used. The Prandtl design normally requires no correction, but must be checked for accuracy.

2. Existing pitot-static tubes must be examined for tip and stem errors so that their constants may be found.

The accuracy of a standard pitot-static tube when inclined to an airstream is shown in Fig. 6. The pitot-static tube can be used only in free air. When the tube is close to a lifting surface, the pressure gradient totally nullifies the worth of the reading as an indication of freestream velocity. It is possible to place the pitot-static tube on an airplane wing so that it makes the airspeed indicator read high at high speed and low at low speed, or vice versa.

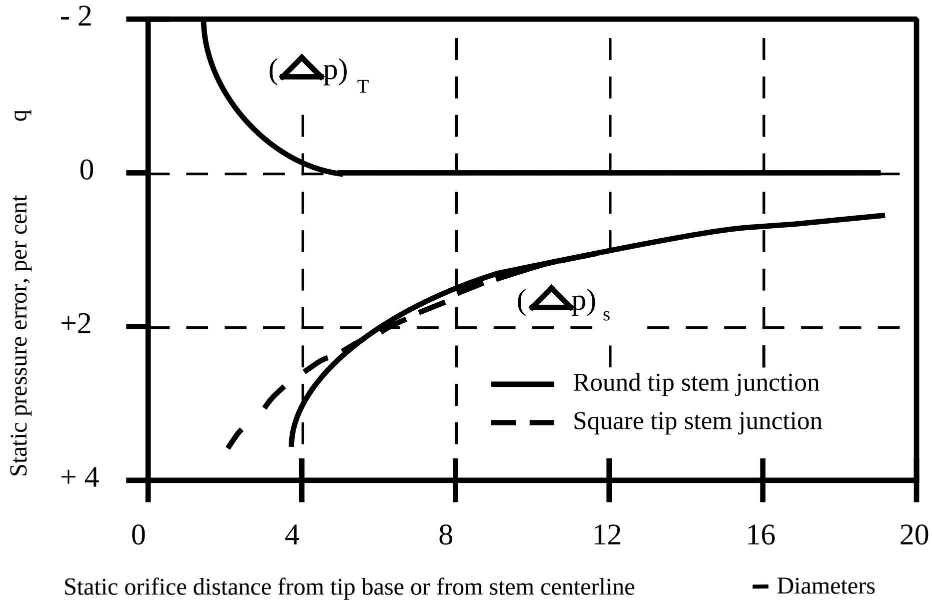

Figure 5. Static pressure errors.

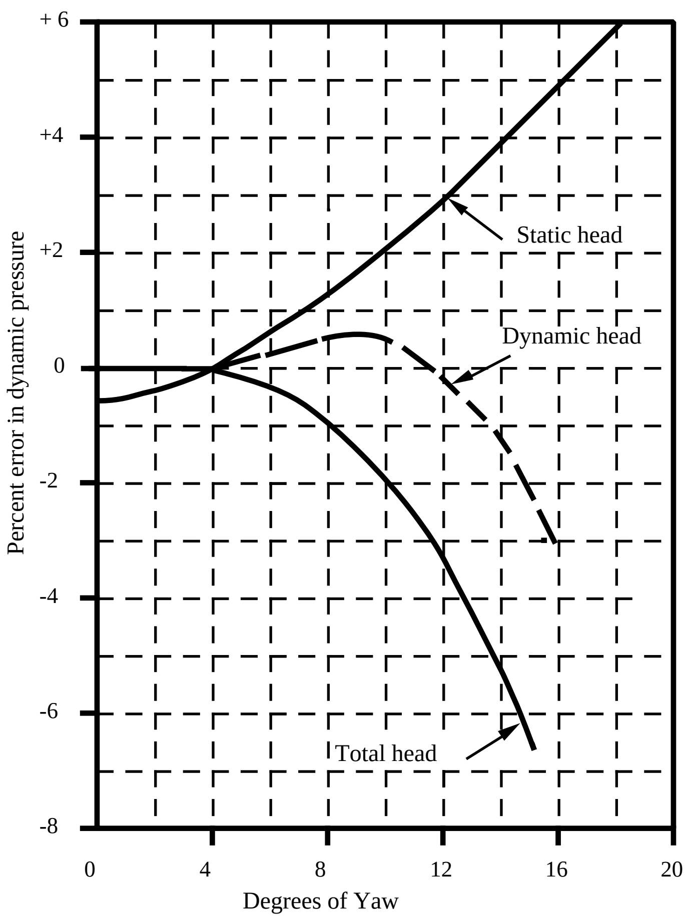

Figure 6. Performance of standard pitot probe in yaw.

Units of Pressure

Because the dynamic pressure measured in the wind tunnel is frequently given in terms of inches of alcohol and q is required in $\mathrm{lb}/\mathrm{ft}^2$, we give the conversion, i.e.

$$
\begin{aligned}
q\Big(\frac{\mathrm{lb}}{\mathrm{ft}^2}\Big) &= (\text{s.g. alc})(\text{specific weight of } \mathrm{H_2O})\Big(\frac{\mathrm{ft}}{\mathrm{in}}\Big)\Delta h(\text{ in alc})\\
q = p_T - p_s = w\Delta h_{\mathrm{alc}} &= \text{s.g.} w_{H_2O}\Delta h(\text{ in alc})\\
&= (0.804)(62.38\frac{\mathrm{lb}}{\mathrm{ft}^2}\frac{1}{12}\frac{\mathrm{ft}}{\mathrm{in}}\Delta h(\text{ in alc})\\
&= 4.18\Delta h(\text{ in alc})\\
&= 4.18q(\text{ in alc})
\end{aligned}
$$

Test Section Velocity – The Tunnel Constant

It is not convenient to insert a pitot-static tube into the test section when a model is in place because

1. it would interfere with the model,
2. it would not yield correct results due to the effect of the model on it.

Thus, some other method of determining the test section dynamic pressure and velocity is required.

Recall that the continuity equation for the steady, one-dimensional flow of a compressible, viscous, homogeneous, continuous fluid streamtube is

$$\dot{m} = \rho A V = \text{const} \tag{11}$$

If an incompressible fluid is assumed and the continuity equation is written between stations 1 and 2, in Fig. 7, we have

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

which for an incompressible fluid, ($\rho = \text{const}$), becomes

$$A_1 V_1 = A_2 V_2 \tag{12}$$

Combining equations (8) and (12), we have

$$p_1 - p_2 = \frac{1}{2}\rho(V_2^2 - V_1^2) = q_2\left[1 - \Big(\frac{V_1}{V_2}\Big)^2\right] = q_2\left[1 - \Big(\frac{A_2}{A_1}\Big)^2\right]$$

and

$$q_2 = \frac{1}{\left[1 - \Big(\dfrac{A_2}{A_1}\Big)^2\right]}(p_1 - p_2) = K(p_1 - p_2) \tag{14}$$

Thus, the dynamic pressure entering the test section, q_2 (or q_∞ for a model), can be directly measured by the differences in static pressure at stations 1 and 2. The positions of stations 1 and 2 in a typical wind tunnel installation are shown in Fig. 7. Station 1 is usually upstream in the settling chamber and station 2 is just far enough upstream of the test section that the model does not influence the readings.

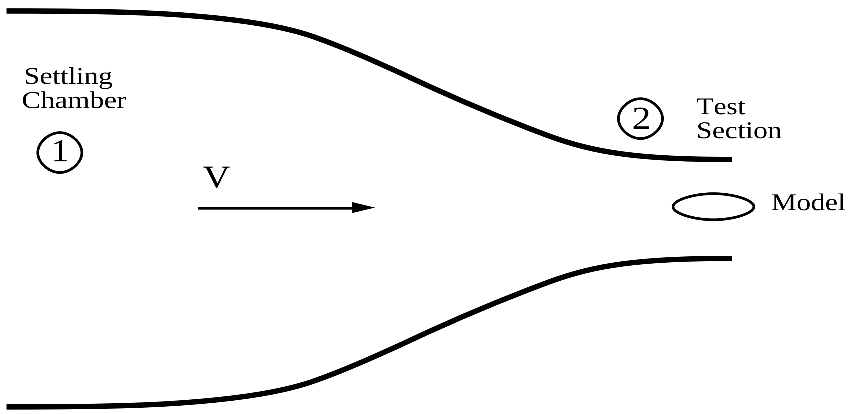

Figure 7. Wind tunnel settling chamber and test section.

The above analysis does not account for frictional (boundary layer and heat) losses between stations 1 and 2. In practice, there is an energy loss/unit volume between stations 1 and 2 due to these effects. Hence, we write

$$p_1 + q_1 = p_2 + q_2 + p_L \tag{15}$$

where p_L = total pressure loss due to friction and after using Eq. (14) we have

$$q_2 = \frac{p_1 - p_2}{\left[1 - \left(\frac{A_2}{A_1}\right)^2\right]} + \frac{p_L}{\left[1 - \left(\frac{A_2}{A_1}\right)^2\right]} \tag{16}$$

or

$$q_2 = q_{2_{\text{theory}}} - p_L$$

Because p_L is always positive

$$\frac{q_2}{q_{2_{\text{theory}}}} < 1 \tag{17}$$

Thus, the actual dynamic pressure entering the test section is less than the theoretical value given by Eq. (14).

Horizontal bouyancy

Horizontal buoyancy refers to the variation of static pressure along the test section caused by the boundary layer growth on the walls. This effect is shown in Fig. 8.

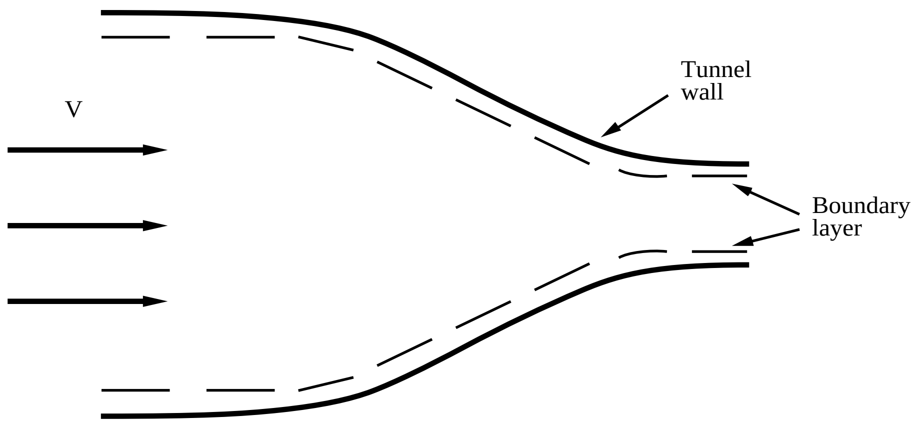

Figure 8. Horizontal buoyancy.

Boundary layer growth reduces the effective area of the test section causing an increase in velocity away from the walls and thus in the measured dynamic pressure at the center of the test section. The magnitude of the two above real fluid effects cannot be accurately calculated. Hence, experimental determination of the tunnel constant is required.

The ratio of the actual test section dynamic pressure obtained by means of a pitot tube to that measured by the static pressure difference between stations 1 and 2 is called the tunnel constant, T.C., i.e.,

$$\text{T.C.} = \frac{q_{\text{act}}}{q_{p_1-p_2}} = \frac{\text{Eq.(9)}}{\text{Eq.(14)}}$$

Fortunately, the tunnel constant varies little over the incompressible range of velocities. Thus, once the tunnel constant is determined it is used to determine the test section dynamic pressure by measuring the static pressure difference between stations 1 and 2.

$$q_2 = (\text{T.C.})q_{2_{\text{theory}}} = (\text{T.C.})K(p_1 - p_2) \tag{18}$$

Turbulence Factor

The disagreement between tests made in different wind tunnels at the same Reynolds number and between tests made in wind tunnels and in flight indicates that some correction is required for the effect of the turbulence produced in the wind tunnel by the propeller, the guide vanes, the vibration of the tunnel walls, etc. This turbulence causes the flow pattern in the tunnel to be similar to the flow pattern in free air at a higher Reynolds number. Hence, the tunnel test Reynolds number called the effective Reynolds number is larger. The increased ratio is called the turbulence factor and is defined by

$$\text{T.F.} \equiv \frac{\text{Re}_{\text{effective}}}{\text{Re}}$$

The turbulence factor is found using a turbulence sphere (Fig. 9) as follows:

The drag coefficient of a sphere is greatly affected by changes in Reynolds number (velocity). Contrary to the laymans guess, C_D for a sphere decreases with increasing airspeed over a certain range of Reynolds numbers because of the earlier transition to a turbulent boundary layer caused by small scale turbulence present in the tunnel. This delays flow separation on the backside of the sphere which results in a smaller wake and hence a decrease in the form or pressure drag. The result is a lower total drag coefficient. The decrease is so rapid in one Reynolds number (velocity) range that both drag coefficient and total drag decrease significantly. The Reynolds number at which the transition to a turbulent boundary layer occurs before flow separation on the sphere is a function of the turbulence already present in the air. Hence, the drag coefficient of a sphere can be used to measure the small scale turbulence in the tunnel. The method used is to measure drag, D, for a small sphere 5 or 6 inches in diameter, at a number of tunnel speeds. After accounting for the horizontal buoyancy, the drag coefficient is computed from

$$C_D = \frac{D}{{}^{1}\!/_{2}\rho V^2 \pi r^2} \tag{20}$$

where r = sphere radius

The sphere drag coefficient is then plotted against the Reynolds number, Re (Fig. 10). The Reynolds number at which the drag coefficient equals 0.30 is determined and called the critical Reynolds number Re_c. This particular value of the drag coefficient occurs in free air at Re $= 385,000$. Thus, it follows that the turbulence factor is

$$T.F. = \frac{385,000}{\mathrm{Re}_c} \tag{21}$$

The effective Reynolds number, $\mathrm{Re}_{effective}$ is then found from Equation (19).

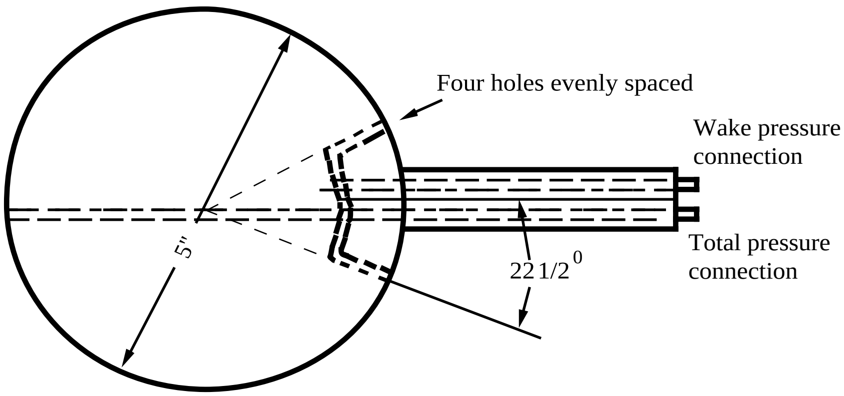

Figure 9. Turbulence sphere.

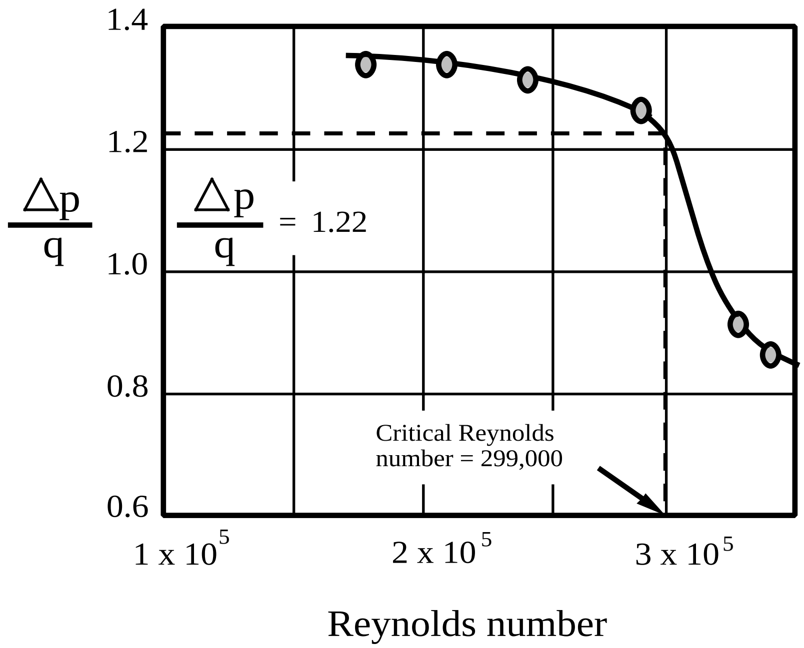

Figure 10. Determining the critical Reynolds Number.

A correlated method of measuring the turbulence in a wind tunnel makes use of a pressure sphere. No force tests are necessary, and the difficulties of finding the support drag are eliminated. The pressure sphere (an ordinary duckpin bowling ball will do) has an orifice at the front stagnation point and four more interconnected and equally spaced orifices at 22½ degrees from the theoretical rear stagnation point. A lead from the front orifice is connected to one leg of a manometer and the lead from the four rear orifices to the other. After the pressure difference due to the static longitudinal pressure gradient (horizontal bouyancy) is subtracted, the resultant pressure difference, Δp, is divided by the dynamic pressure for each Re, and the quotient is plotted against Re (Fig. 10). Tests show that the pressure difference $\Delta p/q$ is 1.22 when the sphere drag coefficient C_D is 0.30. Hence, this value of $\Delta p/q$ determines the critical Reynolds number

In all probability the turbulence factor changes slightly with tunnel speed. If information on this variation is required, it is determined by finding the turbulence factor with spheres of several different diameters.

It is preferable to obtain the turbulence of a tunnel at the speed to be used for testing. This means that the sphere to be used must be the proper size so that the critical Reynolds number occurs at the right speed. All turbulence spheres must be absolutely smooth to be successful.

In order to determine the Reynolds number of the flow, it is necessary to know the density and viscosity. Assuming that air behaves as an ideal gas

$$p = \rho R T \tag{22}$$

or relative to sea level conditions

$$\frac{p}{p_{\text{SL}}} = \frac{\rho}{\rho_{\text{SL}}} \frac{T}{T_{\text{SL}}}$$

and

$$\rho = \frac{p}{RT} = \rho_{\text{SL}} \frac{p}{p_{\text{SL}}} \frac{T_{\text{SL}}}{T} \tag{23}$$

where

$$\begin{aligned}
\rho_{\text{SL}} &= 0.002377 \frac{\text{slugs}}{\text{ft}^3} \\
p_{\text{SL}} &= 29.92 \,\text{in Hg} = 2116.8 \frac{\text{lb}}{\text{ft}^2} = 14.7\text{psi} \\
T_{\text{SL}} &= 518.7^\circ\text{R} = 59^\circ\text{F} \\
R &= 53.3 \frac{\text{ft lbf}}{\text{lbm}\,^\circ\text{R}} = 1716.5 \frac{\text{ft lbf}}{\text{slug}\,^\circ\text{R}}
\end{aligned}$$

Thus, provided that the tunnel is vented to the atmosphere, the air density is obtained from the pressure reading on a barometer outside the tunnel and a thermometer which measures the tunnel air temperature.

The viscosity of air is nearly independent of pressure. The variation with absolute temperature between 300°R and 900°R is approximated by an empirical relationship due to Sutherland called Sutherland's law, i.e.,

$$\mu = 2.270 \frac{T^{3/2}}{T + 198.6} \times 10^{-8} \frac{\text{lb sec}}{\text{ft}^2} \tag{24}$$

with T in °R.

V. Physical Setup

Data for USNA wind tunnels

CCWT ($54 \times 37.5\,\text{in}$)	Eiffel ($44 \times 31\,\text{in}$)
$A_1 = 86.81\,\text{ft}^2$	$A_1 = 90\,\text{ft}^2$
$A_2 = 13.94\,\text{ft}^2$	$A_2 = 9.19\,\text{ft}^2$

VI. Procedure

1. Study the handout and complete the homework assignment prior to the first laboratory period.
2. Measure the pitot-static probe dimensions, i.e., distance from tip-to-static ports, distance from the static ports to the stem and the diameter, in order to correct the data for probe effects.
3. In the laboratory, record barometric pressure, initial test section temperature, and at the conclusion of the test, final test section temperature.
4. With the turbulence sphere installed start the wind tunnel and stabilize at the first inclined manometer reading.
5. Record inclined manometer reading (p_1 and p_2).
6. Record the turbulence sphere pressure p_T and p_{sphere}.
7. Repeat step 3 for inclined manometer settings from 2 to 12 inches of alcohol at 1 inch intervals.
8. Remove the turbulence sphere and install the pitot-static tube in the front test section on the tunnel centerline over the balance center.
9. Start the tunnel and record the total the static pressures of the pitot-static tube p_T and p_s for wall inclined manometer readings from 2 to 12 inches of alcohol at 1 inch intervals.
10. Determine:
    a. An average of value for ρ, T.
    b. For each manometer setting:
        1. Dynamic pressure,
        2. Free-stream velocity,
        3. Reynolds number and effective Reynolds number,
        4. The tunnel constant (T.C.). To obtain the tunnel constant plot q vs $\Delta P_{manoneter}$ where $\Delta P_{manoneter}$ is the reading from the wall manometer.

    c. Tunnel turbulence factor.